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**CELSS RELIABILITY AND PLANT RESPONSE
TO ENVIRONMENTAL STRESS**

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Controlled ecological life support systems (CELSS), using green plants for food, air, and water regeneration, are being designed for long term space exploration. Engineering reliability analysis of a CELSS is needed. A method to apply engineering reliability analysis to the physical and biological components of a CELSS is proposed.

KEYWORDS:

space program, environmental chambers, modeling, quality control, recycle

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Introduction

In order to fully explore space and develop extraterrestrial resources, humans will need to develop the ability to survive indefinitely in space. This will require regenerating adequate supplies of food, water and air, with removal and processing of waste material. In 1978, the National Aeronautics and Space Administration (NASA) started research into controlled ecological life support systems (CELSS) (Averner, 1989). CELSS use green plants to provide food, water, and oxygen, while removing excess carbon dioxide. Laboratory research in CELSS concepts led to the CELSS Breadboard Project being initiated in 1986 at the Kennedy Space Center (Prince and Knott, 1989). The purpose of the Breadboard Project is to show the feasibility of long-term recycling of carbon, nitrogen, water, and air necessary for crew survival.

The primary component of the CELSS Breadboard Project is the Biomass Production Chamber (BPC), a large, closed chamber for plant growth. The chamber is cylindrical, 7.5m high by 3.7m in diameter, and divided in half to create 2 similar chambers. There are a total of four shelves for plant growth, 2 per chamber. Each shelf contains 16 hydroponic trays for a total of 64 trays. Nutrients and water are provided to each shelf from separate 325L tanks. Concentrated nutrients are added as they are taken up by the plants. Nutrient solution pH is controlled by automatic additions of dilute nitric acid. Water transpired by the plants is condensed from the air stream on the cold water coils used for cooling the air. This water is collected, filtered and used to replenish the volume of water in the nutrient tanks. It is also used to make up concentrated nutrient solutions and for supplemental humidification. Lighting is provided by 96 400W high pressure sodium lamps, divided up into 3 per light canopy, eight canopies per shelf. Air is recycled inside the BPC by 2 30kw blowers, 1 per chamber. The atmosphere inside the BPC is automatically enriched with carbon dioxide. Excess oxygen, built up after long periods of chamber closure, is automatically removed using an oxygen concentrator. All of these processes are automatically controlled using a computer, which can be overridden for manual control. Environmental data are

collected by a separate computer with separate sensors. This also provides a check of the control system. For more information on the building and operation of the Biomass Production chamber, see Fortson et al (1992), Wheeler et al (1990), and Prince et al (1988)

NASA has used some regeneration in current and past life support systems, mainly to remove carbon dioxide as it builds up, and in the production of water as a by-product of electricity production in fuel cells. These processes are either physical or chemical processes. Biological processes have not been used by NASA for regeneration in life support systems. In order for bioregenerative life support systems (such as a CELSS) to be used, they will have to compare favorably to existing physicochemical systems. Also, since NASA is primarily an engineering organization, this comparison will be made in engineering terms.

There are several engineering methods of comparing different systems, including cost, effectiveness and reliability. While all of these measures are interrelated, separate measures of each can be made. For example, the cost to build and operate a system can be easily measured, as can the effectiveness of a life support system in providing air and water, while processing waste materials. Reliability of purely physical systems can be accurately measured. However, for a bioregenerative life support system, several of the components rely on biological processes. Traditional engineering methods of measuring reliability have not been applied to biological systems. In order for a comparison to be made of physicochemical and bioregenerative life support systems, engineering methods of measuring the reliability of biological components must be developed.

Reliability

Reliability is defined as the probability of a device operating as planned for a specified length of time under stated conditions (Department of the Air Force, no date). A failure is characterized as the inability of the device to operate as planned or to operate for the specified length of time within the stated conditions. Measuring reliability can be as simple as measuring the length of time for a device to fail. For this information to be useful though, it must be applied to future use of similar systems. This is known as reliability prediction. The U.S. military pioneered early efforts in reliability prediction during World War II as a way to combat high failure rates of field equipment.

Probability distribution functions are used to predict reliability. In general, discrete distributions (based on a countable number of events) are used to predict the number of failures that may occur. Continuous distributions (based on a

random variable that can assume any value within an interval, such as time) are used to predict the time until one failure occurs (McClave and Dietrich, II, 1985). The specific type of distribution (i.e. Weibull, Poisson, Binomial, etc.) is determined for each type of part (Dhillon, 1988). For instance, certain electrical parts have been found by testing and experience to fail over time with a Weibull probability distribution (Department of the Air Force, no date). Failure rates of parts are generally available from the manufacturer, or other industry sources. Knowing when a part will fail allows the use of the correct reliability prediction model. Once it is known how specific parts will fail, the total system reliability can be determined. The reliability measurements for individual parts are combined into a system reliability measure which depends on whether the parts are connected in series, in parallel, or (typically) a combination of both. Parts or components are said to be connected in series when each must function properly for the system to operate. Redundant parts or components, which allow the system to operate as long as either component operates, are said to be connected in parallel.

Systems fail because component parts fail (assuming the operating conditions and function are properly defined). Parts can experience either primary failure or secondary failure. An example of a primary failure is a pump failing to pump water because of frozen bearings. However, if the bearings froze because a valve which supplies the pump with water failed, then the pump has experienced secondary failure. Whether a part experienced primary or secondary failure is important in determining the overall system design and reliability. If the pump is critical to operation and is very reliable by itself, the valve supplying the pump is also critical. It may be that the valve is the most reliable valve available for that application. In that case, redundant valves, and maybe pumps, become imperative. This is the only way to insure the system has the reliability that is required.

Plant Stress and Seed Viability

Physical parts experience stress, and if the stress is great enough, the part will be strained. Salisbury and Ross (1985) use an analogous definition for plants. Biological stress is any change in the plant's environment that might adversely affect plant function. Biological strain is the effected function. Moreover, this strain can be elastic or plastic. Elastic strain is when the decrease in plant function returns to normal when the biological stress is removed. Plastic strain occurs when the plant function remains diminished after the biological stress is removed. While plants generally can tolerate considerable biological stress and strain, the amount of biological stress required for a given amount of plastic and elastic biological

strain needs to be determined in order to determine CELSS reliability.

Plants react to their environment. As an environmental parameter increases, the plant will have no reaction until the parameter reaches a threshold. Above this threshold, plant function will increase, until the environmental parameter reaches a saturation point. Above saturation, the plant function will level off or even decrease. This is a general response to virtually any environmental parameter. Salisbury and Ross list six types of plant response to their environment:

- 1) direct, non-delayed response;
- 2) triggered response;
- 3) delayed response;
- 4) homeostasis;
- 5) conditioning effects;
- and
- 6) carryover effects.

Environmental parameters common to CELSS and to a natural earth environment are light (radiant energy), temperature, carbon dioxide concentration, nutrient availability, water availability, and hydrogen ion availability (pH). Depending on the location of the CELSS, other environmental parameters which might affect plant growth could be different types of radiation, varied (or lack of) gravitational force, and build up of natural and synthetic air pollutants. Each of these parameters, in sufficient amounts, may elicit one or more of the responses listed above. The response may be advantageous or adverse to plant function, or even both. For instance, higher temperature and lower humidity increases plant transpiration (for water purification) and respiration (for oxygen production and carbon dioxide removal). However, these same temperature and humidity settings may reduce the amount of edible plant matter produced. Additionally, the interaction of two or more parameters may elicit a completely different response. A complete discussion of plant response to specific environmental parameters may be found in Larcher (1980).

In the absence of environmental stress and with environmental parameters kept in an optimum range, a crop functions at optimum levels. By genetically selecting a crop from one plant suitable to a given environment, genetic differences are avoided. Therefore, barring external parameters, a crop should function as planned. However, not all plant responses to environmental parameters are known. This can lead to the failure of plants to function as planned (biological strain). Severe biological strain can lead to the loss of the crop. Possible causes for this scenario would be the introduction of an unknown pest or disease, or hidden genetic responses triggered by a combination of environmental parameters. Individual plants can suffer sudden, unexplained loss or dysfunction, but this should not affect the function of the entire crop.

Seed viability, the ability of a seed to develop into a normal, functioning plant, can also affect crop function. Since seed

viability is a phenomena of individual plants, its affect over an entire crop should be limited. Indeed, during the early growth stage of a crop, the effect should be minimal because cultural practices of overplanting and thinning the crop canopy as the crop develops usually allow for the possibility that some early plants will not develop. This is in effect a reliability-based decision, e.g. wheat with a germination rate of 85 percent. Therefore, the main cause of biological strain in plants is caused by failure of the physical system to maintain the proper environmental parameters, or in other words, plants primarily experience secondary failures.

CELSS Reliability

Determining CELSS reliability requires the same information needed for any other system reliability problem; what is the probability that the system (physical parts and plants) will function as planned for the specified length of time within the given parameters (environment)? Determining the reliability of the physical components of a CELSS is straightforward using standard engineering techniques. The failure of a physical part is a discrete event and can be easily measured. Determining the reliability of the biological components is equally straightforward, even though plant response surface curves are nonlinear and continuous. Plant function within a CELSS can still be measured using the same engineering techniques used in analyzing the physical parts. Once the plant function drops below a predetermined level, and cannot return to an acceptable level, this is defined as a failure (a discrete event). Once the probability of occurrence of all of these individual failures are combined, the total reliability of the CELSS is known.

Operational environmental parameters for a CELSS will have to be defined based on which plant function (oxygen production, carbon dioxide removal, water purification, or food production) is most valuable at a given time. To optimize the environment for one particular plant function may be detrimental for another plant function. For the BPC, emphasis is placed on food production, since on a per person level, this is the limiting function among the needed CELSS plant functions. Water purification, oxygen production and carbon dioxide removal in the BPC are all more than adequate for one person, while food production is below that needed for one person.

For the CELSS Breadboard Project, a database of physical failures and maintenance actions on the BPC has been kept since August 1991 (Fortson et al, 1993). While the information gathered is site specific, and the physical system is being continuously modified, the techniques learned are valuable. Figure 1 shows a sample of the output from the database, showing the maintenance time spent on the different BPC subsystems: NDS - nutrient delivery system; ACS - atmospheric control system, or gas system;

HVAC - heating, ventilation and air conditioning system;
CONDENSATE - condensate recycling system; PLC - programmable logic controller, or control system; and MISC - miscellaneous systems, such as lights, door seals, and others. Figure 2 takes the nutrient delivery system (NDS) of the BPC and shows the type of work performed on different components of the NDS. The types of work are defined as follows:

calibration - adjustment of a sensor to optimum operation
maintenance - restore a marginally operating device to optimum performance, exclusive of calibration

replacement - change of an entire component or enough parts so that the component is essentially new (cumulative life of component reset to zero)

repair - work to restore a non-functioning component to normal operation, exclusive of replacement.

Additional information is collected in the database to cover failure rates, types of failures, and criticality of failures. This information is needed to determine what type of probability distribution functions to use when predicting the reliability of the physical parts of the BPC.

More experiments are needed to determine the plant reaction to the biological stresses they are most likely to experience in the BPC. These stresses include high and low temperature, lack of water, lack of light, constant light, high and low pH, and plant pathogens. Complete response surface curves are needed for each of these environmental parameters. Typical plant growth experiments which attempt to identify optimum points of different environmental parameters in terms of plant function are ineffective in identifying extreme points on the response curves. Work has been done in the BPC to develop response surface curves for carbon dioxide uptake and transpiration. More work is needed to develop these curves for other plant functions. Future work on the CELSS Breadboard Project, including the BPC, will be done to test the operation of the system for a given amount of time (12 months) for given levels of operation (water production, food production, oxygen production, carbon dioxide removal). Using these levels of operation for each plant function, and determining where on the plant response surface curve each of these levels lay, the probability of dropping below that level (failure) can be determined. This will be the final piece of information that will allow the total system reliability of the CELSS Breadboard Project to be determined. While this figure will be unique to the Breadboard Project, the techniques used in determining that number will be applicable to any bioregenerative life support system.

Response surface curve information is not only useful in determining the reliability of a CELSS, but also in the design and operation of a CELSS. Since these curves are continuous and not discrete, this can actually enhance the reliability of a

CELSS. During the failure of a physical component in a CELSS, plant functions do not immediately cease, as is the case in a physicochemical system. Instead, there is a gradual decay of plant function which can allow time for maintenance. CELSS design can take this gradual decay into account when planning for redundancy in the subsystems. Also, operational techniques for CELSS, including expert systems, will use this information in short-term planning and in problem resolution. For instance, how much of a decrease in plant function can be tolerated before the CELSS ceases to operate within its specified range? How long can the plants endure loss of temperature control before the proper functioning of the CELSS is lost? Answers to questions such as these are needed in order to build and operate reliable life support systems for space exploration and development.

Summary

The goal of the CELSS Breadboard Project is to build a ground-based prototype of a bioregenerative life support system. In order to fully understand the design and operation of this type of system, and to be able to compare it to traditional physicochemical life support systems, the system reliability must be determined. While standard reliability measurement and prediction techniques can be used on the physical components, new techniques must be developed to produce an engineering analysis of the biological components (plants). The hardiness, or reliability, of the plants will depend on their response to their environment and how well that environment can be maintained. Experiments to measure the complete plant response curve as an environmental parameter is varied to extremes is needed. By combining this information with reliability information on the physical components, total CELSS reliability can be determined.

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BPC SYSTEM ANALYSIS TIME UTILIZATION : JAN 92 - PRESENT

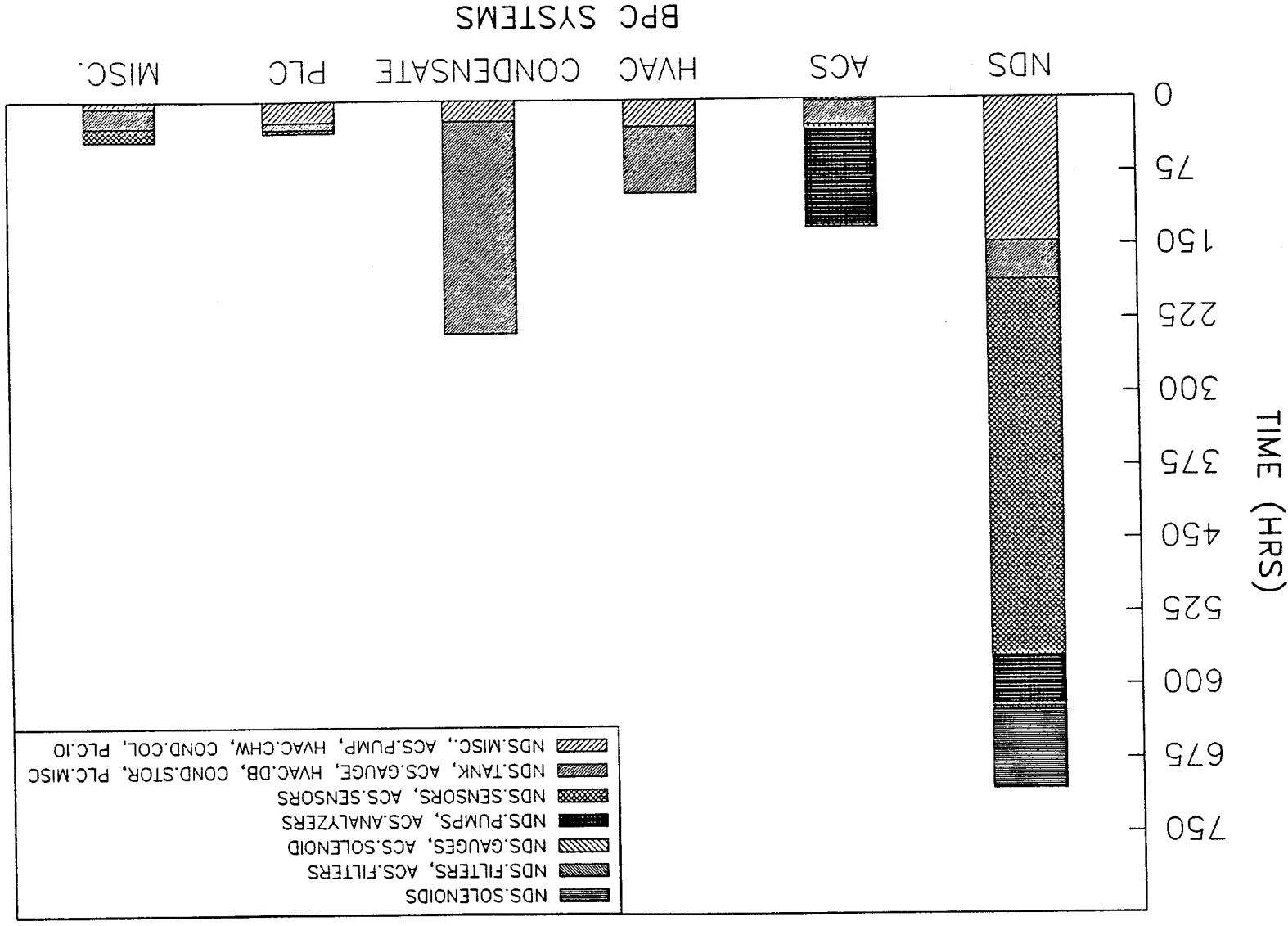


Fig.1 - Sample output of the BPC database showing time spent working on the different BPC subsystems and components.

BPC SYSTEM ANALYSIS: Jan. 92 - Jan. 93

TIME UTILIZATION ON NDS SENSORS

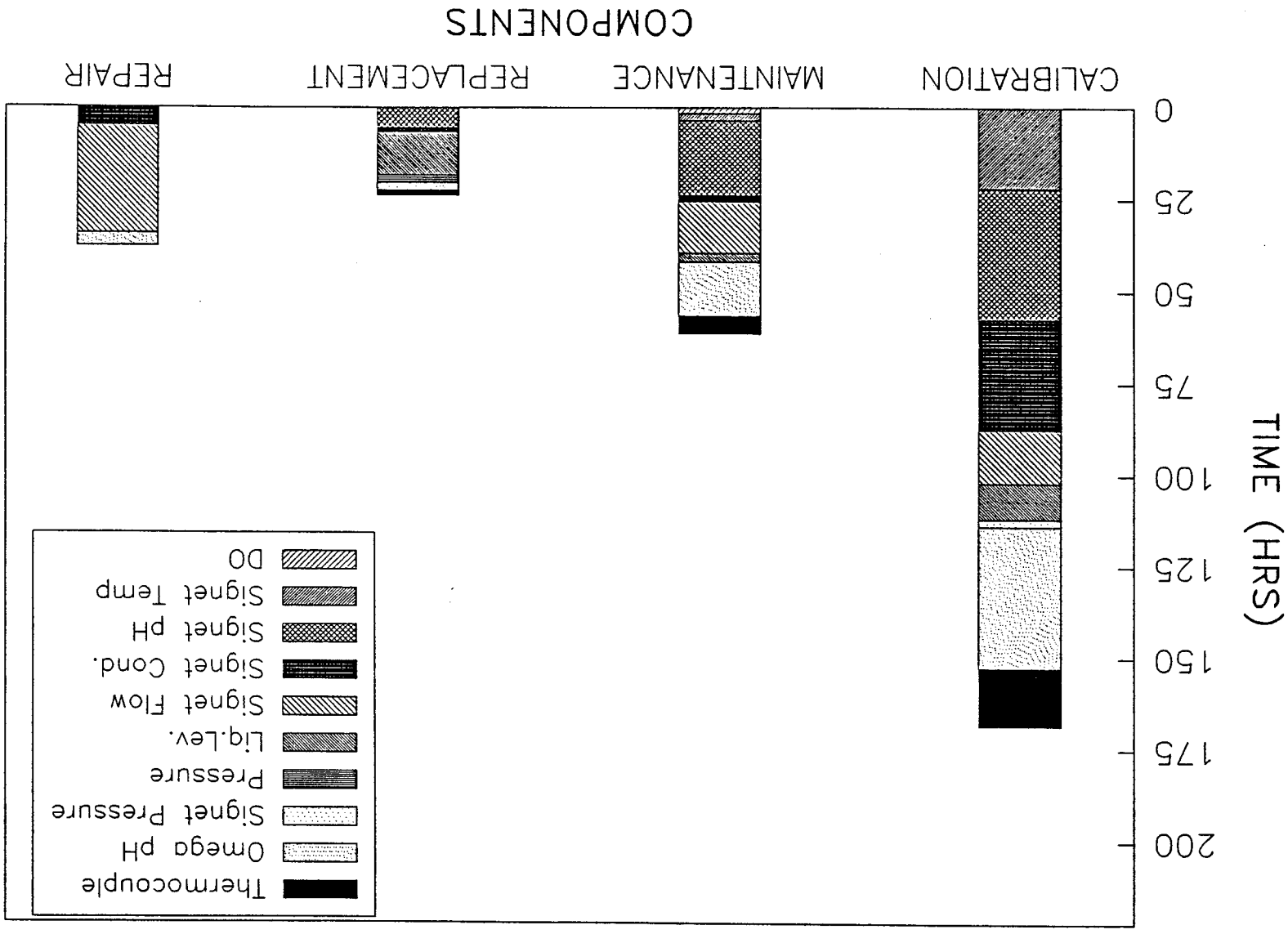


Fig. 2 - Sample output of the BPC database showing time spent working on the sensors of the nutrient delivery system (NDS).